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MANAGERIAL APPROACHES TO SUSTAINABLE CEREAL PRODUCTION IN NORTH MACEDONIA: INTEGRATING CLIMATE-SMART AGRICULTURE, PRECISION FARMING, AND SOIL MANAGEMENT

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Abstract: This paper presents a comprehensive framework for sustainable cereal production, emphasizing the integration of climate-smart agriculture (CSA), precision farming, and effective soil management strategies. As staple cereals like corn, wheat, and rice constitute over 55% of global calorie intake, enhancing their production while mitigating environmental impact is critical for long-term food security. The study explores the role of CSA in adapting to climate change, reducing greenhouse gas emissions, and boosting productivity through innovative technologies such as renewable energy and soil management practices. Precision farming, leveraging data-driven tools like GIS and GPS, optimizes resource use and crop efficiency, contributing to environmental sustainability and economic viability. Additionally, soil and crop management strategies (SCMS) are essential in preventing land degradation, improving nutrient efficiency, and fostering resilient agricultural systems. The paper also examines the specific agricultural conditions and challenges in North Macedonia, where a strategic focus on modernizing production, promoting climate-friendly practices, and enhancing technological adoption is necessary to ensure sustainable cereal production amidst environmental and market disruptions. This multi-dimensional approach offers valuable insights into balancing productivity with ecological sustainability, addressing global food security concerns.

Key words: Sustainable cereal production, Climate-smart agriculture (CSA), Precision farming, Soil management strategies, Global food security

1. INTRODUCTION

Sustainable cereal production involves a holistic approach that optimizes agricultural practices, minimizes environmental impacts, and ensures long-term food security (Marie, 2023). Staple cereals such as corn, wheat, and rice are grown worldwide and form a significant part of the human diet, accounting for more than 55% of the calories consumed globally (Gutiérrez et al., 2018). Sustainable agriculture not only focuses on efficient and productive farming methods but also emphasizes maintaining ecological balance, improving farmers' well-being, and incorporating social and cultural considerations into agricultural practices (Kamakuala, 2024). Scoones et al. (2020) argue that achieving sustainability requires both systemic and structural approaches.

The systemic approach provides a comprehensive framework for understanding sustainability in business, encompassing environmental, social, and economic dimensions. In contrast, the structural approach establishes the management mechanisms necessary to implement the systemic perspective effectively (Scoones et al., 2020).

This study is directed to analyze potential enhance cereal productivity while minimizing environmental impacts and addressing global food security challenges. It focuses on leveraging innovative technologies, optimizing resource use, and fostering resilience to climate change, with a specific emphasis on the conditions and challenges faced by North Macedonia's agricultural sector.

The aim of work was the research analysis of (i) development a comprehensive framework for sustainable cereal production by integrating climate-smart agriculture (CSA), precision farming, and effective soil and crop management strategies (ii) promoting modernized practices, technological adoption, and sustainable policies, (iii) achieving ecological balance, economic viability, and long-term agricultural sustainability.

2. CLIMATE-SMART AGRICULTURE MANAGEMENT STRATEGY

Climate-Smart Agriculture (CSA) is an approach aimed at strengthening agricultural management for sustainability in the face of climate change. It introduces innovative agricultural technologies and practices to enhance production while promoting adaptation to and mitigation of climate change (Muhie, 2022). The concept encompasses a diverse range of practices, including sustainable soil management, efficient water use, crop diversification, and the adoption of renewable energy sources. CSA represents a comprehensive framework that integrates climate change adaptation and mitigation strategies to ensure food security. For instance, employing renewable energy in agriculture-such as pyrolysis units, solar panels, windmills, and water pumps-is critical for enhancing sustainable food production. These technologies not only reduce greenhouse gas emissions but also improve the resilience and efficiency of agricultural systems. The concept of Climate-Smart Agriculture (CSA) encompasses three main pillars: productivity, adaptation, and mitigation. For poor and developing countries, adaptation and productivity are of primary importance, while mitigation efforts are more prominently addressed in developed countries (Hussain et al., 2022). CSA has proven to be an effective approach for improving soil moisture conservation by 12% and increasing grain yield by 66% in maize crops (Mujeyi and Mudhara, 2020).

According to Muhie (2022), CSA for sustainability is built on three main goals: increasing adaptation to climate change, reducing greenhouse gas emissions below business-as-usual levels, and sustainably increasing production and profitability**.** The broader goals of environmental, social, and economic sustainability are also central to organic farming and play a significant role in determining the acceptability of specific agricultural practices (Taylor et al., 2001). Organic farming systems are characterized by respect for the environment and animals, promotion of sustainable farming methods, use of non-chemical fertilizers and pesticides, production of high-quality food products, and avoidance of genetically modified (GM) crops. Despite its potential benefits, the adoption of CSA practices faces significant challenges. Financial constraints, particularly among smallholder farmers, limit investments in CSA technologies even when government subsidies and schemes are available. Moreover, technological gaps and inadequate infrastructure further exacerbate these difficulties, hindering the adoption of precision farming tools and advanced water management systems essential for building climate resilience.

3. MANAGEMENT STRATEGY OF PRECISION FARMING

The management strategy of precision farming is increasingly being adopted as a decision-support system for planning and managing agricultural activities. It utilizes diverse types of data to guide these processes effectively (Perniola et al., 2015).

The primary goal of precision farming is to tailor inputs and agricultural practices to the specific local variability within a field. This strategy relies on evaluating and interpreting spatial variability to manage it efficiently. By doing so, precision farming enhances crop performance, improves environmental quality, and provides feedback on the efficiency and effectiveness of different practices and resource usage. Through location-specific modeling of inputs and crop responses, precision farming significantly improves crop efficiency, reduces costs, and increases overall agricultural output. The adoption of precision farming technology is significant due to its potential for long-term savings, despite initial costs appearing high. Over time, the financial benefits outweigh those of traditional farming practices, enabling growers to determine the minimum required amount of fertilizer and identify the most effective types for specific regions (Georgia, 2022). Precision farming technologies also play a critical role in improving the long-term planning of agricultural operations. By enabling dynamic adjustments to strategies in response to unforeseen circumstances, these technologies provide farmers with the flexibility needed to optimize outcomes (Georgia, 2022).

The implementation of precision farming demands a fundamental shift in farmers' approaches to agriculture. It requires the integration of technological infrastructure, advanced data analysis capabilities, and a deep understanding of agronomy (Anand et al., 2023). Farmers must embrace this data-driven paradigm to maximize crop yields, minimize resource waste, and reduce environmental impact.

In an era of growing global food demand, resource scarcity, and environmental challenges, precision agriculture technology offers a sustainable solution to meet the world's agricultural needs effectively. Precision agriculture incorporates advanced technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) into agricultural practices. These tools enable farmers to manage field variability more effectively, optimizing profitability by moving away from traditional blanket treatments.

One significant advancement in precision agriculture is Variable Rate Technology (VRT), now integrated into agricultural equipment such as fertilizer and pesticide applicators and yield monitors. The rapid development of VRT has been a key driver of precision agriculture's growth, allowing farmers to tailor management practices to specific field locations. This localized approach reduces input usage while maximizing yields, presenting an attractive proposition for farmers (Anand et al., 2023).

Achieving high yields and efficiency depends on sophisticated management of soil and water resources as well as the precise application of inputs. As an integrated approach to field management based on information and technology, precision agriculture enhances agricultural production, productivity, and efficiency while simultaneously minimizing negative environmental impacts.

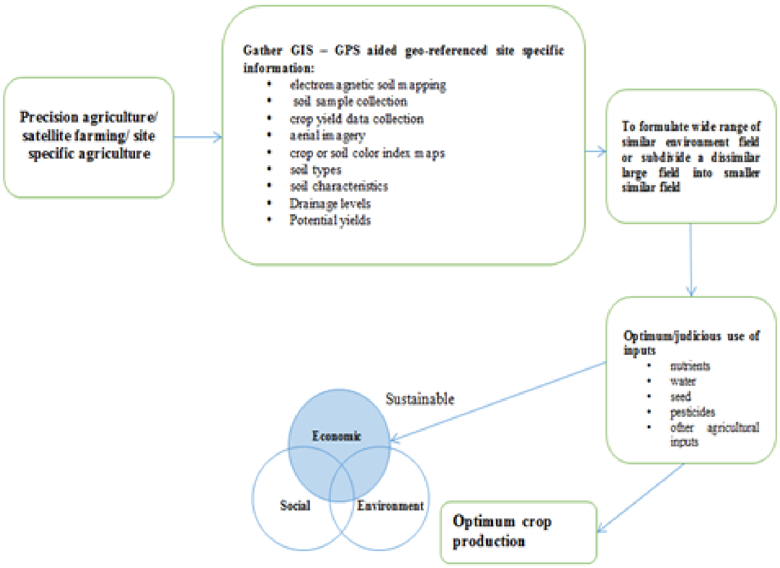

Figure 1. Precision farming for sustainable agriculture (Hossain, 2021)

Achieving high yields and high resource efficiency simultaneously is a widely recognized challenge that requires the integrated application of soil and crop management approaches. Despite the growing global population and escalating food demand, crop yields are stagnating in many regions, and fertilizer use efficiency is declining rapidly (Yokamo et al., 2022). To address these challenges, the Integrated Soil-Crop System Management (ISSM) approach was developed in China. ISSM aims to enhance crop yield and nutrient use efficiency without further increasing chemical fertilizer application, while also mitigating environmental pollution (Zhang et al., 2011). The ISSM paradigm is guided by three core principles: improving soil quality through all feasible and essential measures, ensuring cohesive use of diverse nutrient resources and adequately supplying nutrients to meet crop requirements, and Integrating soil and nutrient management practices with high-yield production systems (Jiao et al., 2018). By aligning soil and nutrient management with sustainable high-yield practices, ISSM offers a pathway to address the dual goals of improving agricultural productivity and protecting the environment.

4. SOIL AND CROP MANAGEMENT STRATEGIES (SCMS)

Agricultural scientists have long recognized that soil management practices are not only vital for maximizing agricultural production but also crucial for mitigating environmental pollution (Shinde and Sirsath, 2020). Soil and Crop Management Strategies (SCMS) aim to enhance crop productivity and prevent land degradation by optimizing various soil properties-biological, physical, chemical, and hydrological-through balanced nutrient management (Esilaba et al., 2005). SCMS are guided by two key principles: **matching input quantity with crop demand** to ensure efficient resource use and **synchronizing nutrient application with crop growth stages** to optimize timing and effectiveness (Shah and Wu, 2019).

These strategies not only improve crop yields but also conserve soil resources and protect the environment (Cui et al., 2014). Effective SCMS focus on preventing soil erosion, a major contributor to land scarcity, while adopting practices that avoid soil contamination and degradation. Soil erosion by water and wind is a primary process that degrades the surface structure of exposed soil, resulting in the loss of nutrient-rich topsoil. This significantly reduces soil fertility and undermines sustainable agricultural practices. By addressing both erosion and contamination, SCMS offers a sustainable approach to improving agricultural productivity while preserving environmental health. Recent research has shown that land degradation is expected to continue due to the significant increase in global GDP by 2050. To ensure future food security, sustainable soil management through efficient nutrient management and appropriate soil conservation practices presents some of the key challenges (Shinde and Sirsath, 2020).

Effective policies are essential for promoting sustainable soil management. By establishing soil quality standards, land use regulations, and incentives for the adoption of sustainable practices, governments can encourage farmers to implement soil conservation measures and mitigate land degradation (Turpin et al., 2017).

Additionally, government subsidies, grants, and tax incentives for sustainable practices-such as cover crops, agroforestry, and organic farming-are crucial for supporting farmers' investment in soil health (Turpin et al., 2017). Furthermore, policies that promote farmer education, extension services, and knowledge exchange platforms significantly enhance awareness and encourage the adoption of sustainable soil management practices (Amundson, 2020).

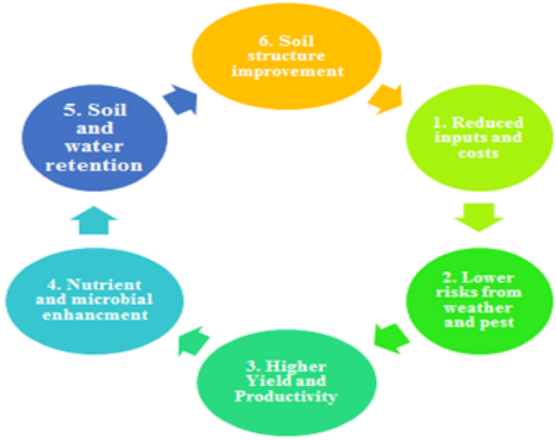

Figure 2. Importance of soil health and management (Srivastava et al., 2024)

5. CEREAL PRODUCTION CONDITIONS IN THE REPUBLIC OF NORTH MACEDONIA

According to data from the State Statistical Office, agricultural land in the Republic of North Macedonia covered 1.256.854 hectares in 2022. In 2023, there was a slight decrease, with the total area falling to 1.250.821 hectares. The sown area in 2022 covered 275.297 hectares, while in 2023, it decreased to 269.834 hectares. The largest share of the area under arable land and gardens is devoted to cereals, with a total of 158.798 hectares sown in 2022. However, in 2023, this area decreased to 156.469 hectares.

Table 1. Cultivated and Sown areas in Republic of North Macedonia (www.stat.gov.mk)

Year	Agricultural area (ha)	Total sown areas (ha)	Cereals (ha)
2022	1.256.854	275.297	158.798
2023	1.250.821	269.834	156.469

In terms of cereal production, wheat and corn account for the largest share of total production. According to an analysis of wheat and corn production over the past five years, the highest production levels were recorded in 2020 for both crops, with each subsequent year showing a continuous decline.

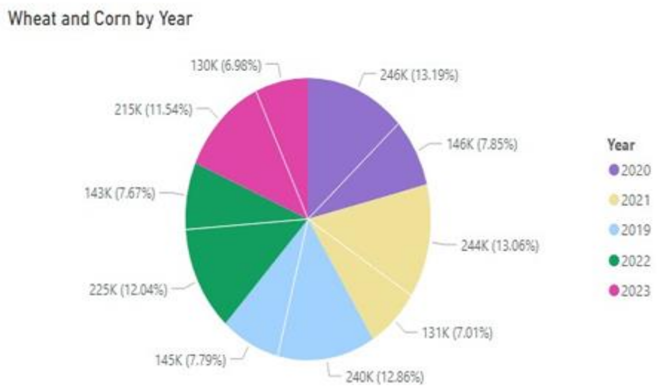

Figure 3. Production of Wheat and Corn in Republic of North Macedonia by Year (www.stat.gov.mk)

When analyzing corn production by region and year, the highest production in the Republic of North Macedonia occurred in 2020, with a total of 146.434 tons. This was followed by a decline in 2021, then an increase in 2022. However, in 2023, corn production reached its lowest point in the entire five-year period. Regarding corn production by region, the Polog region leads in production, followed by Pelagonia, East, Southeast, Skopje, Southwest, Northeast, with the lowest production occurring in the Vardar region.

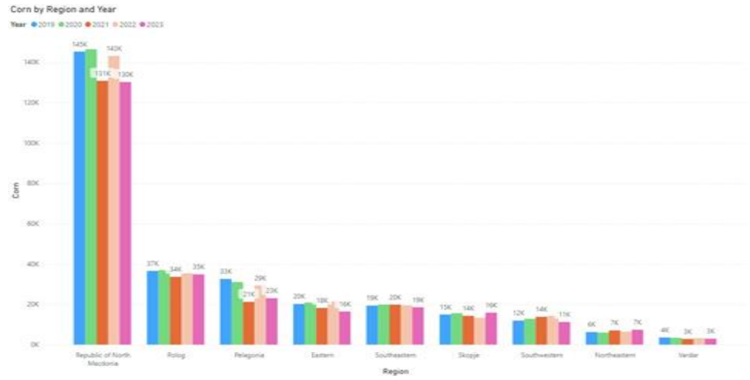

Figure 4. Production of Corn by Region and Year (www.stat.gov.mk)

When analyzing wheat production by region and year, the highest production in the Republic of North Macedonia occurred in 2020, with 246.031 tons. This was followed by a continuous decline, with the lowest production in 2023 compared to the entire five-year period. Regarding wheat production by region, the highest production is in the Pelagonia region, followed by the Northeast, Skopje, Vardar, Southeast, East, Polog, and the lowest production in the Southwest region.

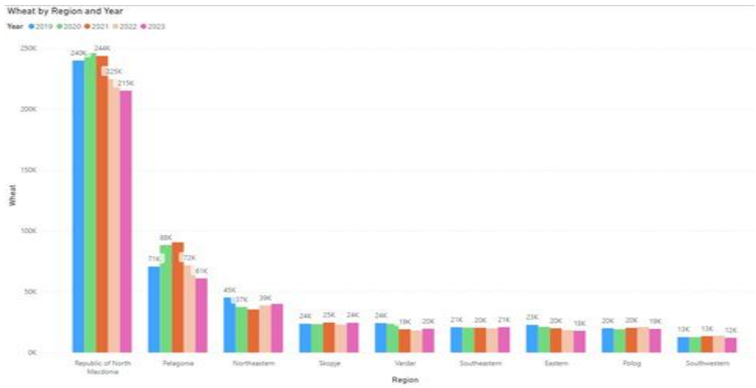

Figure 5. Production of Wheat by Region and Year (www.stat.gov.mk)

6. STRATEGY OF THE REPUBLIC OF NORTH MACEDONIA FOR ADDRESSING AGRICULTURAL CHALLENGES AND INCREASING CEREAL PRODUCTION

The Strategy is the third document in the Republic of North Macedonia of its kind that systematically outlines the policies to be implemented, offering solutions for addressing both current and future challenges. Agriculture is one of the most sensitive sectors to the negative impacts of climate change, and crises caused by new animal and plant diseases are becoming increasingly frequent.

The general goals for the sector include improving the competitiveness and sustainability of agricultural income, applying ecological practices in production to reduce the impact of climate change and adapt to it, and ensuring the sustainable development of rural areas-all supported by the state. Based on the identified weaknesses in wheat production, there is a need to maintain income support that sustains the current level of production, reduce production costs, and increase yields, especially in the face of increased negative climate impacts that primarily affect productivity.

In the event of market disruptions and a drop in purchase prices below the cost of production, intervention measures are legally prescribed in accordance with the law. These measures have thus far been applied only in the form of aid for storage in state warehouses. However, other interventions require simplification of procedures.

Approximately 38 percent of the country is prone to severe soil erosion due to topographic features and heavy rainfall, although in many cases, soil erosion is also caused by unsustainable agricultural practices. The objectives of the strategy include increasing agricultural production through modernization to better meet domestic consumption with local production, improving the quality of Macedonian agricultural products with added value, ensuring food safety and animal welfare, and creating conditions for a competitive and sustainable agriculture sector in both domestic and foreign markets.

Special emphasis is placed on introducing policies that were neglected in the past, particularly those aimed at building human capacity for the adoption of new technologies. The newly established Knowledge and Innovation System will connect all stakeholders in the creation of innovations, knowledge transfer, and digitalization. It also facilitates the exchange of digital technologies, smart agriculture, and production methods based on knowledge and good governance. The negative perception of modern technologies among farmers should be addressed through efficient advisory services, demonstration farms, and training programs designed to encourage the acceptance of new technologies. To mitigate and adapt to climate change, climate-friendly practices will be promoted through their inclusion in cross-compliance requirements and increased co-financing of necessary investments. Farmers will receive support through appropriate advisory packages on best practices and training to reduce the impact of climate change. Policy interventions aimed at protecting soil from degradation will include strict adherence to cross-compliance requirements for soil cover, erosion protection, and support for investments in precision agriculture. This will involve using sensors for the optimal application of agro-technical measures and providing financial support for agro-environmental initiatives.

Precision agriculture, which tailors the use of water and fertilizers to crop needs, will be promoted through operational programs of producer organizations, supported by the Agricultural Knowledge and Innovation System. This will include dedicated advice and training. Income support for grain and fodder crops will help maintain the current level of production, especially in the face of increased negative climate impacts that primarily affect productivity.

Given the importance of wheat for ensuring food security, direct payments will continue in the next period, with higher amounts allocated to producers who achieve higher yields. To increase average yields of crops and meet the needs of existing areas, special support measures, along with an advisory package for the adaptation of advanced technologies, will be introduced. For the restructuring of the agri-food sector, which faces an unfavorable structure and needs modernization, the following interventions are planned: investments in the modernization and diversification of the technological processes of existing agri-food businesses, including support for crop production modernization and the exploitation of production potential in controlled conditions. Special attention will be given to implementing innovative technological solutions and production systems. In addition to investments aimed at improving physical capital, significant attention should be given to enhancing standards, both by adapting the legislative framework and by establishing an effective control system.

Interventions in the technical and technological improvement of the agricultural sector require the mobilization of a wide range of entities, including advisory services, scientific and research institutions, and other stakeholders. A broad array of general measures to support agriculture is needed, along with the establishment of various forms of administrative and technical support to encourage collaboration among these entities. The agricultural advisory system should incorporate the economic, environmental, and social dimensions of managing agricultural holdings and land, enabling the transfer of information on modern technological advancements and innovations from science.

State-supported services should assist farmers and other beneficiaries of national agricultural policy in understanding the relationship between farm management, land management, and the application of specific standards, especially those related to the environment and climate. Due to the benefits for preserving crop growth, yield, and income, it is expected that farmers will more readily accept measures for adapting to negative climate effects. Additionally, the introduction of measures to mitigate climate change impacts will be encouraged through a greater number of instruments in national agricultural policies.

7. CONCLUSION

In conclusion, sustainable cereal production requires a multi-faceted approach that incorporates innovative practices such as Climate-Smart Agriculture (CSA), Precision Farming, and Effective Soil and Crop Management strategies. These practices are crucial for enhancing productivity while minimizing environmental impacts, ensuring long-term food security, and adapting to the challenges posed by climate change. The integration of modern technologies, such as renewable energy and data-driven farming tools, can significantly improve efficiency, reduce resource use, and promote resilience in agricultural systems. However, the successful implementation of these strategies depends on overcoming challenges such as financial constraints, technological gaps, and insufficient infrastructure, especially in developing regions.

In the context of Republic of North Macedonia, the government's strategic focus on modernizing agricultural practices, fostering technological adoption, and mitigating climate change impacts is vital for enhancing cereal production and achieving sustainability. Continued investment in training, advisory services, and climate-friendly policies will support farmers in adopting sustainable practices and improving yields. Ultimately, fostering collaboration between farmers, government bodies, and research institutions will be key to developing a resilient and sustainable agricultural sector that can meet global food demands while preserving environmental integrity.

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